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D.L. Spittlehouse, R.S. Adams, and R.D. Winkler

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ABSTRACT

The Sicamous Creek research site is 7 km east-southeast of Sicamous (50° 50' N, 119° 55' W) at an elevation of 1530–1830 m, on a northwest-facing slope. The Engelmann spruce–subalpine fir forest (ESSFwc2) is 22–27 m tall and canopy closure is about 50%. The climate at the site of the Sicamous Creek Silvicultural Systems Project is cool and moist with a mean annual air temperature of 1.2°C and an annual precipitation of 910 mm, about half of which occurs as snow.

The treatments monitored in this study were 0.1-, 1-, and 10-ha openings and mature forest. The base weather station was in a large opening with scattered regeneration adjacent to the experimental area. This study, in agreement with other studies, shows that most of the change in microclimate from forest to opening takes place within one tree height either side of the forest/opening edge. Openings of less than one tree height in diameter have a solar, wind, and thermal environment similar to that in the forest. Edge orientation has an effect, particularly for south-facing edges, where solar radiation can penetrate some distance into the forest for much of the day. Wind blowing directly into an edge penetrates farther into the forest than from other directions. The forest intercepts 20–30% of the precipitation. On sunny days, the forest air temperature near the ground is 2–4°C cooler than in the large openings. Near-surface daytime soil temperature is also 2–4°C cooler in the forest, while near-surface nighttime soil temperatures are similar.

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RESEARCH REPORT

24

Forest, Edge, and Opening Microclimate at Sicamous Creek

D.L. Spittlehouse, R.S. Adams, and R.D. Winkler

2004

BRITISH COLUMBIA

Ministry of Forests
Forest Science Program

1 INTRODUCTION

The study described in this report was part of a larger project established in 1990, the Sicamous Creek Silvicultural Systems Project (Vyse 1997, 1999). The larger project is intended to address public and professional concerns about the effects of clearcut harvesting on high-elevation forests in the southern interior of British Columbia. The objectives of the study reported here were:

- to provide weather data for the Sicamous Creek Silvicultural Systems Project.
- to perform intensive, brief experiments to determine the variation in time and space of weather variables not amenable to long-term monitoring.
- to obtain measurements of microclimate at various positions across a forest edge and within openings of various sizes.
- to validate models of solar irradiance, wind fields, and microclimate across a forest edge and in openings.

Much of the current interest in forest edges is concerned with how far the inner edge extends into the forest (Figure 1). This is due primarily to the concern about maintaining biodiversity in a fragmented landscape, and providing a buffer against a changed microclimate (e.g., riparian buffer strips). However, there is an interest in the outer edge (in the clearing)

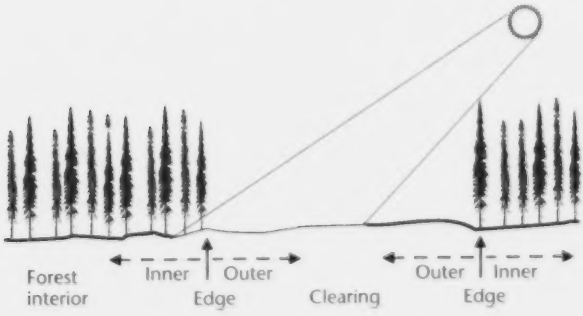

FIGURE 1 *Schematic of the inner and outer edges of the forest–clearing boundary.*

because this is where regeneration of the next stand occurs, and, as clearcuts become smaller, the proportion of landscape consisting of outer edge also increases.

The study started with the installation of the Sicamous Creek weather station in a large opening near the camp in July 1993. This was followed in 1996–1998 with the intensive measurements of edge microclimate. Energy balance and wind flow measurements were made in 1996 and 1997 in cooperation with researchers from the University of British Columbia. Wind gust measurements were made in 1997 and 1998 as part of a study on blowdown. The Sicamous Creek weather station continues to function, and data analysis, reporting, and extension activities are continuing.

2 REVIEW

2.1 MICROCLIMATE OF FOREST AND OPENING

Microclimate below forest canopies and in forest openings has been studied extensively for decades (FAO 1962; Reifsnyder and Lull 1965; Jarvis et al. 1976; Rauner 1976; Geiger et al. 1995; McCaughey et al. 1997; Chen et al. 1999). The presence or absence of a canopy directly influences the amount of solar, photosynthetically active, and longwave radiation, the wind speed, and precipitation near the ground. Differences in these variables influence the air temperature and humidity regime and the soil temperature and moisture regime of the forest, edge, and openings.

Solar radiation transmission through forest canopies depends on the height of the crown and the density and arrangement of foliage elements (Vézina and Pech 1964; Reifsnyder and Lull 1965; Federer 1971; Black et al. 1991; Canham et al. 1999). Reduction in solar radiation under forest cover ranges from more than 90% with dense canopies (Young and Mitchell 1994; Chen et al. 1995; Brosofske et al. 1997) to 50–70% in open stands (Reifsnyder and Lull 1965; Orlander and Langvall 1993). The forest canopy changes the spectral distribution of light because plant foliage differentially absorbs and reflects the various wavelengths (Vézina and Boulter 1966; Federer and

Tanner 1966; Atzet and Waring 1970; Yang et al. 1993). There is a greater reduction in the ultraviolet and photosynthetically active radiation ranges compared to longer solar radiation wavelengths. There are also some subtle differences in below-canopy spectral distribution between hardwood and coniferous canopies.

Longwave radiation to the forest floor increases as the canopy cover increases because the forest canopy is usually much warmer than the sky being blocked (Reifsnyder and Lull 1965; Cochran 1969; Carlson and Groot 1997). Although this increase somewhat offsets the reduction in solar radiation below the forest, net radiation below forest canopies is usually substantially lower than that in the open, although the difference is somewhat reduced when there is a snowpack. The high level of snow reflectivity greatly reduces the solar radiation component of the net radiation.

The radiation regime in small openings varies throughout the day and year, depending on the extent of the shadow of the surrounding forest. The area of the opening in shade depends on the height of the surrounding trees and the size of the opening. The effect of the trees on downward longwave radiation in the opening decreases with distance away from the edge, and is negligible by about one tree height into the opening (Reifsnyder and Lull 1965; Cochran 1969).

The amount of precipitation intercepted by the forest depends on the canopy cover (Calder 1990; McCaughey et al. 1997; Pomeroy and Goodison 1997; Spittlehouse 1998a, b; Winkler 1999). Annual interception losses vary from 10 to 30%, and the fraction of precipitation intercepted decreases as storm size increases. The time since the previous storm, and the weather conditions during the current storm, both affect interception. Winter precipitation not intercepted and lost through sublimation from high-elevation forests is stored on the ground as snow. In spring, snowmelt is influenced by the weather, and by forest cover, including the distribution of gaps in the canopy (Woo et al. 2000). Forest cover can reduce snowmelt rates by up to 60% of those in the open, depending on stand characteristics (Winkler 1999; Winkler et al. 2004).

Forest canopies tend to reduce the diurnal air temperature range compared to large open areas. Maximum differences (opening minus forest) in daytime air temperature at the 1.5–2 m height vary from 3 to 6°C or more (Williams-Linera

1990; Young and Mitchell 1994; Chen et al. 1995; Cadenasso et al. 1997; Brosofske et al. 1997; Potter et al. 2001; Stathers et al. 2001). At night, forest areas are typically about 1°C warmer than in the open (Chen et al. 1995), although Brosofske et al. (1997) found temperatures about 1°C cooler above a stream. Surface and near-surface soil temperatures show the largest differences between forest and open sites, being up to 10–15°C cooler under forest canopies during the daytime and 1–2°C warmer at night (Chen et al. 1995; Brosofske et al. 1997; Stathers et al. 2001).

The vapour pressure of the air is mainly a function of the surrounding airmass and will be similar in the open and in the forest. Consequently, the relative humidity and vapour pressure deficit will depend on the air temperature. The lower daytime forest air temperature means that relative humidity is 5–25% higher in the forest (Williams-Linera 1990; Chen et al. 1995; Brosofske et al 1997). Wind speed beneath the forest canopy is commonly reduced to below the resolution of most anemometers (Raynor 1971; Chen et al. 1995).

2.2 MICROCLIMATE OF EDGE

The microclimate at the forest edge is a transition between the conditions of the forest interior and the open. Several studies (Table 1) in a wide range of forest types and climate have shown that much of the change in microclimate takes place within a distance equal to the mean height of the dominant and co-dominant trees (15–60 m) either side of the edge. These differences could influence plant growth near edges. For example, Groot and Carlson (1996) reported less frost damage to seedlings near the edge of small openings as a result of longwave radiative shielding. York et al. (2003) found increased height growth of seedlings on the north edge of small openings that was correlated with the increase in light levels relative to the south side (northern hemisphere site). Čienciala et al. (2002) and Taylor et al. (2001) found an increase in water use by trees at the edge of a large opening compared to interior trees, and ascribed this to the different edge microclimate.

Solar radiation, wind speed, and soil temperatures change

from opening to interior forest conditions more rapidly than do air temperature and relative humidity. Edge orientation has an effect, particularly for a south-facing edge, where solar radiation penetrates some distance into the forest for much of the day. There is usually less difference in temperature between the east and west edges than between the north and south edges. The transition from forest to clearing occurs mostly within the clearing, except at the north edge where the change occurs mainly in the forest. This happens because the north edge receives full sun most of the day, and sunlight penetrates into the forest (Chen et al. 1993; Young and Mitchell 1994; Cadenasso et al. 1997). Wind blowing directly into the edge penetrates farther into the forest than from other directions (Raynor 1971) and could result in raised temperatures up to three tree heights into the forest (Chen et al. 1995). Klassen et al. (2002) found a small enhancement of turbulent energy fluxes over a forest downwind of the edge, and ascribed it to the disturbance of wind flow by the edge.

3 SITE DESCRIPTION

The research site is located south of the north fork of Sicamous Creek, 7 km north of Mount Mara and 7 km east-southeast of Sicamous (50° 50′ N, 119° 55′ W) at an elevation of 1530–1830 m. The area is classified as Engelmann Spruce–Subalpine Fir, wet cold (ESSFwc2) (Lloyd et al. 1990). The forest is 35% Engelmann spruce and 65% subalpine fir with 264 $m^3 ha^{-1}$ live timber and 30% of standing trees as snags (Vyse 1997, 1999). The dominant trees are 22–27 m tall, and canopy closure is about 50%. The treatment area is on a northwest-facing slope and the base weather station is to the west in a large opening with scattered regeneration (Figure 2). The treatments monitored in this study were 0.1-ha opening (C3), 1-ha opening (B4), 10-ha opening (B5), and forest (adjacent to B5). Details are presented by Spittlehouse and Adams (2001). Information from research at the Opax Silvicultural Systems Study and from the Penticton Creek Watershed Experiment is also included in the report.

TABLE 1 *Studies describing the microclimate of adjacent forests, edges, and openings*

Forest	Opening	Location	Reference
Conifers, hardwoods	Meadows	Central Europe	Research from 1930s–1950s cited in Geiger et al. (1995) pp. 298–308
Red and white pine, 10.5 m, closed canopy	Grass field	New York State	Raynor (1971)
Lodgepole pine, 20–25 m	0.03–1 ha circular clearcuts	Southwestern Alberta	Golding and Swanson (1986)
Tropical forest, 30–50 m	Pasture	Panama	Williams-Linera (1990)
Norway spruce and Scots pine, 22–25 m, varying density	Grass covered	Sweden	Örlander and Langvall (1993)
Douglas-fir and western hemlock, 55–65 m	10- to 15-year-old clearcut, brush and trees ≈ 2 m tall	Washington State	Chen et al. (1993a, b, 1995)
Mixed podocarp-broadleaf	Pasture	North Island, New Zealand	Young and Mitchell (1994)
Amazonian rainforest, 30 m	Pasture and bush	Central Amazonia, Brazil	Camargo and Kapos (1995)
Aspen, 19 m, 40 years old	0.01–1.5 ha strip and circular clearcuts	Ontario	Groot and Carlson (1996), Carlson and Groot (1997)
Conifers	Clearcuts	California	Ledwith (1996)
Hardwoods, mixedwood, 80–100 years old	Clearcuts	Maine	Hagan and Whitman (2000)

Oak, birch, beech, and maple, 60+ years old	Pasture	New York State	Cadenasso et al. (1997)
Douglas-fir and western hemlock, 26–60 m	1- to 4-year-old clearcuts	Washington State	Brosofske et al. (1997)
Engelmann spruce and subalpine fir, 20–27 m; lodgepole pine, 4–6 m	Large clearcuts	Southern interior, British Columbia	Winkler (1999), Winkler et al. (2004)
Broadleaf rainforest, 20 m	Pasture	North Island, New Zealand	Davis-Colley et al. (2000)
Aspen	8-ha recent clearcut	Wisconsin	Potter et al. (2001)
Engelmann spruce and subalpine fir, 20–30 m	0.03–1 ha square clearcuts	Central interior, British Columbia	Stathers et al. (2001)
Blue gum, 14 m, 7 years old	Pasture and wheat	South Australia	Taylor et al. (2001)
Scots pine, 10–14 m, 70 years old	20-year-old clearcut	Northern Sweden	Cienciala et al. (2002)
Japanese larch, 19 m	Bog	Northeast Netherlands	Klaassen et al. (2002)
Engelmann spruce and subalpine fir, 22–27 m	0.01–10 ha square clearcuts	Southern interior, British Columbia	Huggard and Vyse (2002), Redding et al. (2003), this study
Sierran mixed conifer forest, 27–34 m	0.01–1 ha circular clearcuts	California	York et al. (2003)

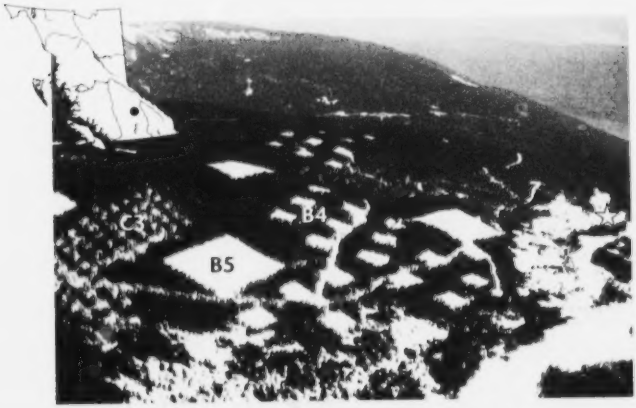

FIGURE 2 *View from the northeast of the Sicamous Creek Silvicultural Systems Project block layout. The monitored treatment units are 0.1-ha openings (C3), 1-ha openings (B4), 10-ha opening (B5), and forest (adjacent to B5). The star on the right indicates the base weather station.*

4 MEASUREMENTS

4.1 WEATHER STATION

The Sicamous base weather station was established in July 1993 in a 500-ha opening with scattered regeneration, on a gentle slope, at an elevation of 1570 m, 200 m southeast of the Sicamous Creek camp (Figure 2). Solar radiation, photosynthetically active radiation (PAR), air temperature and humidity, soil temperature, wind speed and direction, liquid precipitation, snow temperature, and snow depth were monitored using a data logger (Appendix 1). Hourly averages and totals, and daily averages, maximum and minimum values, and totals were collected. Environmental and human-caused failures in recording resulted in data gaps. Relationships developed between the base station and other weather stations were used to fill in the missing data. The British Columbia Forest Service fire weather station #2209, 15 km north of the research site at 1250 m elevation, was used for filling in missing May–September daily

temperature, and monthly relative humidity, rainfall, and wind speed. The Upper Penticton Creek Watershed Experiment at 1620 m elevation, 130 km south of Sicamous Creek, was used for monthly winter air temperature and humidity, solar radiation, and snow depth. Details are presented by Spittlehouse and Adams (2001).

4.2 MEASURING AND MODELLING SOLAR RADIATION IN FOREST AND OPENING

Solar radiation is dominant in the energy balance of the surface. Measurements of diffuse radiation at Sicamous (Huggard and Vyse 2002) and transects of photosynthetically active radiation across the edges of a 1-ha opening at the Opax Silvicultural Systems Study (D.L. Spittlehouse and L. Paterson, unpublished data) are presented here.

The Opax site is a 1-ha opening in an interior Douglas-fir forest with about 60% canopy cover. Transects were made across the north and south edges under clear and partially cloudy conditions using a PAR sensor. Three point measurements, spatially separated by 3 m, were made at each location and the ratio of below-canopy PAR to that in the middle of the opening was calculated. The CLIMO model (Chen et al. 1993) was used to calculate light levels across openings of different sizes. CLIMO is based on canopy clumping at the scale of tree, branch, and shoot; it can take account of the time of year, and has been validated for clearings in complex terrain and on steep slopes.

4.3 ULTRAVIOLET-B RADIATION

Measurements were made at the centre of the B5 10-ha opening at 1750 m. UV-B (280–320 nm) was measured using a broadband UV-B radiometer (Solar-Lite Company Inc., Philadelphia, PA, model 501) at 10 m above the ground. The spectral response of the instrument is matched to the Diffey erythemal action spectrum (McKinlay and Diffey 1987). Hourly mean values were determined from 60-second samples, and out-

put was recorded in minimal erythemal dosage (MED) units and then converted to energy units (mW m^{-2} nm^{-1} and kJ m^{-2} d^{-1}). Solar radiation was measured at the same location with a thermopile pyranometer (Eppley Laboratories model B&W). Both instruments were monitored with a data logger at 60-second intervals, and daily UV-B dosages and daily total solar irradiance were calculated by integration of the hourly mean values. No correction was made for the small reduction in diffuse UV-B irradiance due to the reduction in the sky-view factor by the ridge to the south.

The response of living cells to ultraviolet radiation is dependent on the frequency of the radiation and the dosage in quantum units. Caldwell (1971) developed a generalized action spectrum for plant material in the UV-B spectrum based on the quantum response of cells and organelles. The Green weighting function (Bjorn and Teramura 1993) is used to convert from a quantum response to energy response. Conversion of the Sicamous Creek data to the Green function and evaluation of the effects of changing ozone thickness requires knowledge of the spectral distribution. The broad-band instrument assumes a spectral distribution based on an ozone column thickness of 270 Dobson units. Correction factors were developed using the spectral distributions for the normal ozone column thickness using the Diffey weighting and spectra measured on Saturna Island by the Meteorological Service of Canada. Trapezoidal integration of the spectra gave UV-B irradiance in weighted units of mW m^{-2} nm^{-1}. The increase in UV-B irradiance expected from a 20% reduction in ozone column thickness is similar for all three weighting functions (1.36–1.43). When converting mW m^{-2} nm^{-1} Diffey weighted to the Green weighted normalized to 300 nm, the Diffey value must be increased by 1.65 for normal ozone levels or by 1.73 for low ozone levels.

4.4 ENERGY BALANCE IN OPENING

Fluxes of net radiation, soil heat, sensible heat, and water vapour were measured at three locations in the B5 10-ha opening during 1996 and 1997. Eddy-correlation systems were installed at 25, 50, and 200 m from the western edge of the 10-ha opening in an east–west line. Each station had two 1-D sonic anemom-

eters (Campbell Scientific Incorporated [CSI] model CA-27), a net-radiometer (Micromet Systems model Q*6 and Q*7), and soil heat flux plates (home-made). Two krypton hygrometers (CSI model KH-20) were placed at 200 m to measure water vapour flux. An inter-comparison of instruments at the same location gave excellent agreement between the sensible heat flux density measured by the six sonic anemometers.

4.5 WIND SPEED IN OPENING

Field measurements took place in the 10- and 0.1-ha openings (Novak et al. 1997; Orchansky et al. 1997). Towers, 8-m tall, were established along the west–east mid-line of the 10-ha opening at 25, 75, 125, 200, 250, and 300 m from the west edge. The 0.1-ha clearing, located 300 m north of the 10-ha clearing, had a tower in the centre. A wind speed and direction anemometer (RMYoung 05103) was mounted at about 25 m by climbing a tree between two 1-ha openings, topping the tree, and mounting the instrument at the top. Maximum gusts were evaluated using 1-, 10- and 60-second integration periods. Wind speed and direction anemometers were scanned at 5 Hz, and wind statistics were recorded half-hourly and daily. Wind tunnel studies were conducted in the University of British Columbia Department of Mechanical Engineering large blow-through wind tunnel using a model forest consisting of 15 cm high individual tree models simulating Engelmann spruce trees at a scale of 1:200 and a density equivalent to 500 stems ha^{-1}. Instantaneous wind speed was measured across scale models of 10- and 0.1-ha openings with a tri-axial hot-film constant temperature anemometer (Novak et al. 1997; Orchansky et al. 1997).

4.6 PRECIPITATION AND SNOWMELT IN FOREST AND OPENING

In 1997 and 1998, snow depth and snow water equivalent (SWE) were measured at 111 survey points throughout the 10-ha opening and into the adjacent forest along a north–south and a west–east transect. Three measurements were made at each

point and averaged to provide SWE at -25, -12, -6, 0, 6, 12, 25, 50, and 100 m from the forest edges and in the centre of the opening (negative distances indicate position within the forest). Measurements were made using a standard Federal snow tube near the time of maximum accumulation (April 1) and during snowmelt (late May or early June). A Campbell Scientific Incorporated SR50 depth gauge was used to determine the daily snow depth at the weather station in the middle of the 10-ha opening during winter 1996/97. The data logger also monitored two snowmelt lysimeters that measured meltwater outflow from the base of the snowpack. The lysimeter boxes were fibreglass-covered plywood (2.4 × 1.2 × 0.15 m), draining into large tipping buckets.

Rainfall interception was not determined at Sicamous but was measured in two high-elevation Engelmann spruce–subalpine fir and lodgepole pine forests in the dry, cold ESSF, 1620 m elevation, at the Upper Penticton Creek Watershed Experiment (Spittlehouse 1998b). Five 6 × 0.1-m, V-shaped troughs and five stemflow collectors drained into tipping buckets monitored continuously with a data logger.

4.7 AIR AND SOIL TEMPERATURE IN FOREST AND OPENING

Transects of soil and air temperature were installed from forest through the north, south, east, and west edges and into the 0.1-, 1- and 10-ha openings. Measurement locations for the 1- and 10-ha openings were -25, -12, -6, -3, 0, 3, 6, 12, 25, and 50 m (negative distances indicate position within the forest) from the edge. The 0.1-ha transect terminated at 12 m into the opening. Air temperature was measured at 1.5 and 0.2 m above the ground, and soil temperature at 0.07 m below the surface. Commercially available sensors and radiation shields can have radiation errors of 2–3°C. Radiation errors were minimized using 30-gauge chromel-constantan thermocouple wire without a radiation shield. Even with these small sensors, the error can be up to 1°C under full sun and low wind speed. Soil temperature measurement is not subject to radiation errors but can have large spatial variability. Each soil temperature sensor consisted of three thermocouples and swamping resistors

connected in parallel to give a three-point average. Sensors were read at 60-second intervals using a data logger and multiplexer on each edge transect; hourly and daily values were recorded.

Profiles of air and near-surface soil temperature were measured in the forest near the 10-ha opening during the summer of 1997. Thermocouples were placed at 27, 18, 9, 6, 3, and 1.5 m above and 0.07 m below the soil surface. The base weather station in the large opening had thermistors or thermocouples at 5.5, 3, 1.5, and 0.25 m above and 0.01, 0.15, and 0.5 m below the soil surface (Appendix 1).

5 RESULTS

5.1 SICAMOUS CREEK CLIMATE

The climate at Sicamous is cool and moist (Table 2). The mean annual air temperature is 1.2°C and mean daily temperature varies from 10°C in summer to -6°C in winter. Extreme daily maximum temperatures of 23–30°C occurred in summer, and extreme minimum temperatures of -25 to -36°C occurred in mid-winter. Soil temperature near the surface varies from 0°C during the winter to more than 20°C during the summer. The temperature range is much reduced at the 0.5-m depth, varying from 1 to 10°C. A wide range of air temperature conditions was experienced during the measurement period. The coldest winter temperatures were recorded in 1996, while 1998, an El Niño year, had an exceptionally warm spring and summer.

The wettest year (1280 mm of precipitation) was 1997, and 1998 the driest (700 mm) during the measurement period. Mean annual precipitation for the period is estimated to be 910 mm (Table 2). Summer (June–September) rainfall averaged 320 mm, with only 1998 having a dry summer (22 mm of rain in July and August). Permanent snow cover starts in late October and the maximum depth of the snowpack occurs in late March. There is a large inter-annual variation in the amount of snow, with annual maximum depth varying from 1.3 to 2 m during 1994–2002 (Table 3). Snowmelt begins in late April and snow cover disappears anytime from mid May to early June. Winter 1998/99 had the longest snow season and one of the deepest

TABLE 2 *Climate data for 1994–2002 for the base station in a 500-ha opening adjacent to the experimental area. PAR is photosynthetically active radiation, T_{max} is average daily maximum temperature, T_{min} is average daily minimum temperature, Ext is the period extreme, vpd_{max} is average maximum vapour pressure deficit, and $Wind_{Max}$ is average daily maximum wind speed over 1 minute. Ta0.25m is the 0.25 m maximum and minimum air temperature, and Ts0.15m and Ts0.5m are the average daily 0.15 and 0.5 m soil temperatures. Monthly winter precipitation data are not available. Snowpack depth on April 15 was converted to water equivalent assuming a density of 0.35 Mg m^{-3} and added to the May to October precipitation record to get an estimate of annual precipitation. Solar radiation (MJ m^{-2} d^{-1}) = PAR*0.488.*

	PAR (mol $m^{-2}d^{-1}$)	T_{max} (°C)	T_{min} (°C)	ExtT_{max} (°C)	ExtT_{min} (°C)	vpd_{max} (kPa)	Ext vpd_{max} (kPa)	$Wind_{Max}$ (m/s)	Precipitation (mm)	Ta0.25m $_{max}$(°C)	Ta0.25m $_{min}$(°C)	Ts0.15m avg(°C)	Ts0.50m avg(°C)
Jan.	4.9	-1.9	-11.5	9.1	-41.1	0.1	0.7	4.5	---	-0.2	-0.6	0.5	1.2
Feb.	10.4	-0.9	-11.7	12.5	-33.2	0.2	0.9	5.3	---	-0.1	-0.6	0.3	0.9
Mar.	18.8	1.4	-9.4	15.6	-28.0	0.3	1.3	5.5	---	0.0	-0.2	0.3	0.8
April	30.0	6.2	-6.4	18.8	-20.7	0.5	1.8	5.6	---	0.3	-0.1	0.2	0.6
May	36.1	10.6	-2.1	23.4	-13.5	0.7	2.3	5.4	79	4.5	-0.2	1.2	1.1
June	39.3	14.2	1.3	27.2	-4.0	0.9	2.6	5.3	96	17.6	1.4	7.4	6.2
July	42.9	18.2	4.0	30.2	-7.3	1.3	3.9	5.4	91	22.6	3.6	10.4	9.1
Aug.	37.4	18.0	3.6	29.2	-4.9	1.3	3.4	5.2	64	22.0	2.2	10.4	9.6
Sept.	27.5	14.4	0.1	27.0	-8.9	1.0	2.9	5.2	69	17.8	-0.5	8.3	8.3
Oct.	12.9	5.5	-4.5	18.2	-20.0	0.4	1.6	4.8	85	5.3	-2.3	4.0	5.0
Nov.	5.3	0.7	-7.9	12.6	-27.5	0.2	1.6	4.5	---	-0.3	-2.2	1.1	2.1
Dec.	3.3	-3.2	-12.3	8.9	-41.8	0.1	0.5	3.9	---	-0.8	-1.8	0.6	1.4

Mean annual temperature 1.2°C Mean annual precipitation 910 mm

TABLE 3 *Depth of snow on ground (m) on the first of the month in the highest (1998/99) and lowest (2000/01) snowfall winters during 1994–2002 at the base station. Date at which snowpack started to accumulate and date it disappeared are shown.*

	High snow (m)	Low snow (m)
Start	Oct 8	Oct 30
Nov	0.08	0.01
Dec	0.51	0.33
Jan	1.23	0.80
Feb	1.49	1.12
Mar	1.66	1.28
April	1.57	1.11
May	1.14	0.79
June	0.39	0
Gone	June 11	May 31

packs, peaking in early March 1999. At the start of spring melt, snow water equivalent averages 430 mm.

Minimum relative humidity averages 40% during the summer and 70% in winter. The resulting daytime vapour pressure deficits are typically 1–2 kPa in summer, with extremes of over 3 kPa in some years. Wind tends to come from the southwest–west sector and the northeast–southeast sector. Wind is seldom from the north or south. The site is dominated by gentle, thermally generated valley winds for much of the year, flowing eastwards up the valley during the day and westwards down the valley at night. Even large-scale flows due to major weather systems are aligned with the valley. There is no difference in wind patterns between summer and winter. No intense windstorms occurred at the Sicamous Creek site between 1994 and 2002.

5.1.1 Ultraviolet-B radiation

The peak daily UV-B dosage at Sicamous Creek, with normal ozone column thickness, was approximately 9.5, and the average daily dosage, approximately 5.5 kJ m^{-2} d^{-1} (Green weighted, normalized at 300 nm). The Sicamous Creek

site has about two-thirds of the potential total solar radiation during the summer due to the high frequency of cloud. There is a higher proportion of UV-B in the diffuse component compared to solar radiation. Differences in the diurnal trend of solar and UV-B irradiance means that the relationship between hourly solar and hourly UV-B are non-linear. However, the daily UV-B dosages and daily total solar radiation were linearly related. Data from June 14 to July 19, 1997 gave UV-B=0.39+0.16*Solar (kJ m^{-2} d^{-1} Diffey weighted), with daily total solar radiation in MJ m^{-2} d^{-1}, adjusted R^2 = 0.88, and standard error of 0.35 kJ m^{-2} d^{-1}. This equation was used to estimate UV-B dosages for all years from 1993 to 2002 using measurements of solar radiation made at the base weather station. Daily peak dosage never exceeded 6 kJ m^{-2} d^{-1} (Diffey weighted) and no indication was found that UV-B irradiance was systematically higher in any years. The mean daily UV-B dosage for the period June 1–July 31 never exceeded 3.8 kJ m^{-2} d^{-1} (Diffey weighted).

5.1.2 Comparison of the base station climate and experimental area climate

The Sicamous Creek experimental site is 1500 ha, with a 300-m elevation difference between the base station and the uppermost treatment units. During the winter, mean daily air temperatures in the B5 10-ha opening are similar to those at the base station. However, from April to September the higher elevations are 2°C warmer than the base station. Maximum temperatures are similar but the base station averages 4–5°C cooler than B5. Differences of up to 10°C occur on clear calm nights. The differences are due to the topography of the site. At night, katabatic winds reduce the effect of radiative cooling by helping to move the cooled air off the slopes to the flatter valley bottom where it ponds. Most of the treatment blocks are on similar slopes and aspects, and would be expected to have similar conditions. A possible exception is the C3 10-ha opening, which has a complex topography. No major differences were found between the base station and B5 for wind speed, daytime humidity, solar radiation, and rainfall. There is a greater depth of snow and a delay in disappearance of the pack by 1–2 weeks in the treatment blocks. The topography may result in a greater catch of snow, and the northwesterly aspect results in a lower amount of

radiation for snowmelt. In summary, there is no large topoclimatic variation across the Sicamous Creek experimental site.

5.2 MICROCLIMATE OF FOREST, EDGE, AND OPENING

5.2.1 Conceptual model

Microclimate (e.g., air temperature, soil temperature, and soil moisture) is a result of the absorption and loss of energy and precipitation at the surface. In a forest edge, the energy comes from sunlight; a portion is absorbed by a surface (either the forest canopy or the clearing surface) and the rest is reflected. The absorbed energy increases the temperature of the surface and is transported away by wind (sensible heat flux), conducted down into the soil (soil heat flux), and used to evaporate water from the soil surface or for plant transpiration (latent heat flux). Energy is also lost from the surface as longwave (thermal) radiation. The microclimate can be predicted by considering the partitioning of these fluxes. For example, during the daytime the conceptual model predicts that the warmest place in a clearing will be near the edge facing the sun. Wind speed at the edge is lower than toward the centre and the edge receives more solar radiation than the centre because some is reflected from the trees at the edge. Similarly, the coolest point will be near the edge facing away from the sun. Most studies of edge microclimate are consistent with the conceptual model outlined above and with the results described below.

5.2.2 Solar and photosynthetically active radiation

Distributions for solar and photosynthetically active radiation are similar and will be discussed together under the term "light." Figure 3 shows the typical light regime in 0.1- and 1-ha openings and adjacent forest. The trees shade most of the small opening for much of the day. Solar radiation penetrates up to 20 m into the north edge (south facing). Shading effects extend up to 20 m (one tree height) into the south side of the opening (north-facing edge). The CLIMO model calculations show that openings need to be greater than two tree heights wide to have more than 50% of the area with light levels >90% of that above

the canopy (Figure 4). Aspect results in an increase in area in full sun for south-facing slopes compared to a horizontal surface, and a substantial decrease for north-facing slopes.

5.2.3 Sensible and latent heat fluxes

Wind-tunnel experiments predicted that a gradient in sensible heat flux density should occur across the opening due to variations in wind speed and turbulence as the wind moved across the opening. However, no consistent variation in sensible heat-flux density could be detected across the opening (Appendix 2). There was a tendency for higher fluxes at the 200-m location with westerly winds. Sensible heat flux measured with a 3-D sonic anemometer was used to confirm that the slope of the clearing was not adversely affecting the 1-D anemometer measurements. The latent heat-flux density was low, probably because the clearing was mainly unvegetated and the soil surface was dry, thus reducing soil evaporation. The daytime Bowen ratio varied from 0.8 to 1.2. This is consistent with other values for a partially revegetated clearcut (Adams et al. 1991).

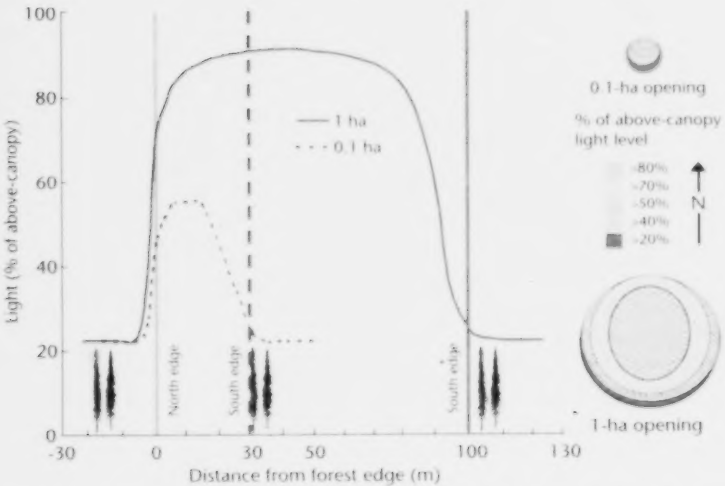

FIGURE 3 *Fraction of solar radiation in the forest, and in the 0.1-ha and 1-ha openings, for a north–south transect on a northwest-facing slope and the distribution of radiation within the 0.1- and 1-ha openings as a percentage of that above the canopy.*

5.2.4 Wind speed

Openings of less than 0.1 ha have wind speeds similar to those in the forest (Orchansky et al. 1997). In larger openings, the wind variation away from the edge depends on the wind direction (Figure 5). Measurements of wind speed across clearings of different sizes in the field and in the wind tunnel are in excellent agreement when topographic features are considered. Wind speed is of importance because of concerns about blowdown of trees. Daily average maximum wind speeds are 5–6 m s^{-1}. These are sustained winds over 60 seconds. The highest hourly mean wind speed recorded since July 1993 was 5.5 m s^{-1} (19.8 km h^{-1}), which is quite low compared to the values for coastal sites. Blowdown is related to the maximum gust speed. Maximum gusts were evaluated using 1-, 10- and 60-second integration periods, and the maximum gust speeds are close to a Weibull distribution. The 60-second integration

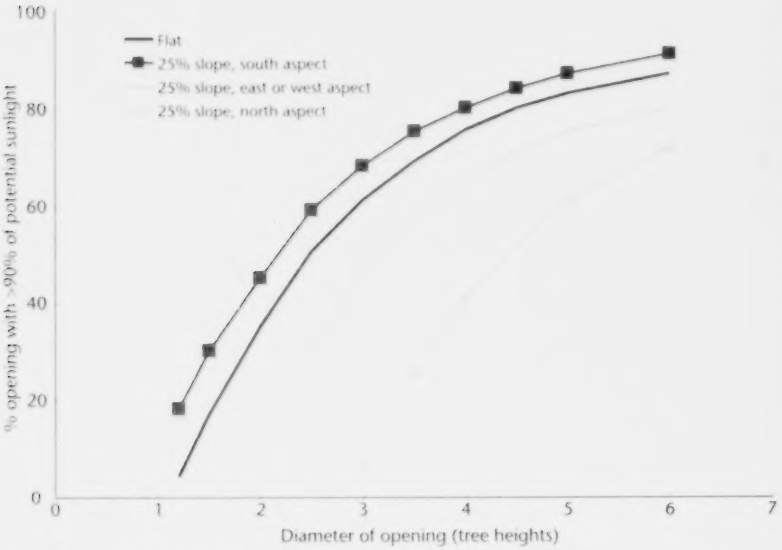

FIGURE 4 *Influence of opening size on fraction of area with sunlight >90% of that above the canopy for a flat surface and for north, south, and west/east aspects with a 25% slope. Opening size is expressed as tree height. Data obtained using the CLIMO model (Chen et al. 1993).*

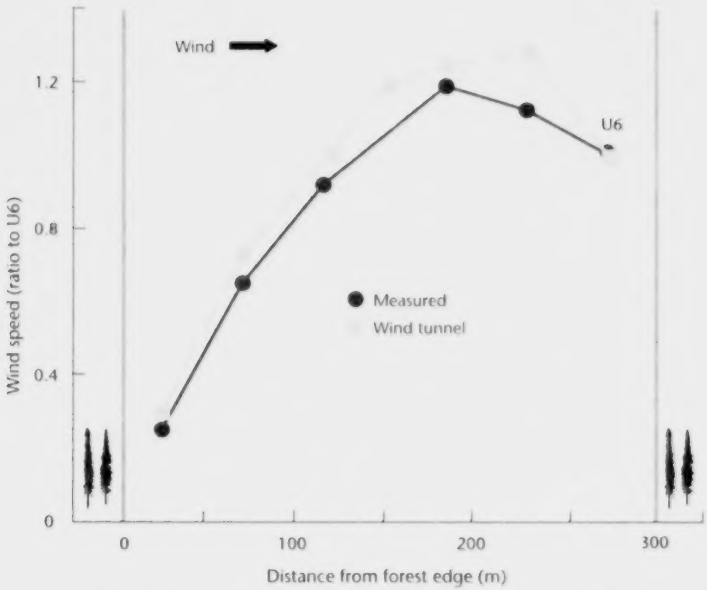

FIGURE 5 *Wind speed measured in the 10-ha opening and simulated in a wind tunnel relative to the measurement (U6) near the east edge. Based on data in Orchansky et al. (1997).*

period resulted in lower indicated gust speeds. The similarity between the 10- and 1-second integration periods indicates that the duration of gusts must be between 10 and 60 seconds. The maximum gust recorded over two lengthy periods (July 1993–December 1994 and December 1997–October 1998) was 15 m s^{-1}. There were no major windthrow events during the experimental period at Sicamous Creek.

5.2.5 Precipitation interception and accumulation

Over the summer, about 24% of the rainfall was intercepted in the high-elevation forests at Upper Penticton Creek. This is consistent with data for interior and coastal forests reported elsewhere (Spittlehouse 1998a) and similar values are expected at Sicamous. About 30% of the snow was intercepted by the forest canopy, consistent with data for other interior of British Columbia forest sites (Winkler 1999). Snow water

equivalent (SWE) was found to be highly variable across the 10-ha opening and into the forest along all transects. The pattern of snow accumulation along the transects was consistent over the 2 years surveyed, which had winters of high (1996/97) and low (1997/98) snowfall. The effect of the edge on snow accumulation extended for up to 25 m into the clearcut (April 1 in Figure 6).

5.2.6 Snowmelt

In 1997, snowpack ripening occurred over a period of roughly 10 days once average daily air temperatures remained above 0°C (Figure 7). By mid-May, the snow lysimeters measured water draining from the base of the snowpack at rates of 10–60 mm per day, depending on the weather. Melt rates are consistent with data reported by Winkler et al. (2004). As with snow accumulation, little difference in snow ablation was observed between the west and east edges, except that the slightly higher accumulations of snow were retained longer for roughly 50 m farther into the opening from the east edge than the west (Figure 6). Dramatic differences in snow ablation were observed between the north and south edges. Snow was retained

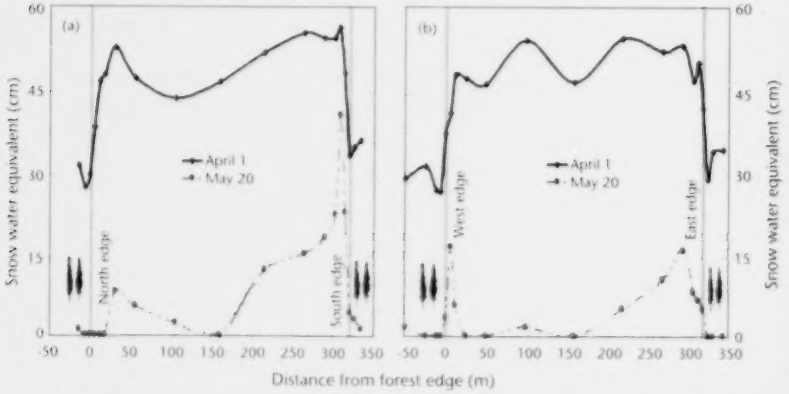

FIGURE 6 *North–south (a) and west–east (b) transects of snow water equivalent, from the forest across the 10-ha opening, near the time of maximum accumulation (April 1) and during snowmelt (May 20), 1998. Snow depth in the middle of the opening on April 1 was 1.4 m. Similar patterns were obtained in 1997, but, with a delayed melt season, the equivalent melt pattern occurred in early June.*

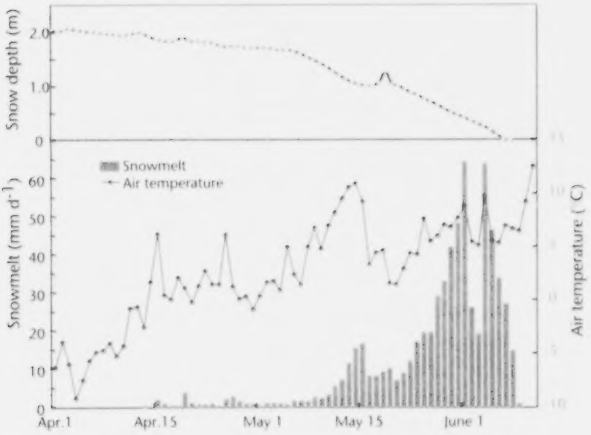

FIGURE 7 *Snow depth (m) (upper panel), and snowmelt (mm d^{-1}) and air temperature (°C) (lower panel), from April 1 to June 12, 1997 in the centre of the 10-ha opening.*

much later in spring along the south edge than the north, and into the opening for approximately 200 m from the south edge. These data are consistent with those reported at other study sites (e.g., Golding and Swanson 1986; Satterlund and Adams 1992). The patterns in snow ablation observed in the 10-ha opening are also consistent with results expected as a result of increased solar radiation and longwave radiation along the north (i.e., south-facing) edge, and the similar amounts of energy for snowmelt available at the west and east edges.

5.2.7 Air humidity

The warmer daytime air temperature in the large opening results in the relative humidity being 5–10% lower than in the forest. Edge effects on humidity are similar to those of air temperature (discussed below).

5.2.8 Air and soil temperature

The temperature transects across each edge in the 10-ha and 1-ha openings (Figures 8, 9, and 10) show similar patterns, and these patterns are similar to those of light distribution

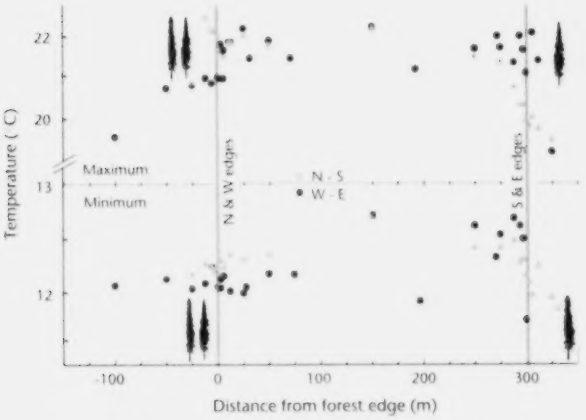

FIGURE 8 *Daily maximum and minimum air temperature on north–south and west–east transects from the forest through the 10-ha opening, August 20, 1997.*

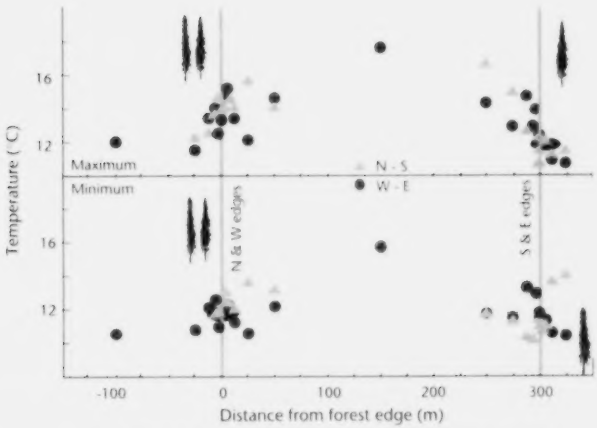

FIGURE 9 *Daily maximum and minimum soil temperature on north–south and west–east transects from the forest through the 10-ha opening, August 20, 1997.*

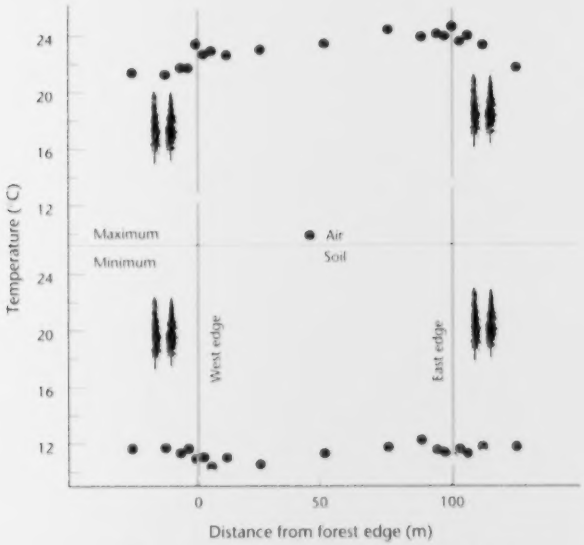

FIGURE 10 *Daily maximum and minimum air and soil temperature on a west–east transect from the forest through the 1-ha opening, August 9, 1997.*

(Figure 3). This is due to the fact that net-radiation distribution, which determines the microclimate, is similar to the pattern of light distribution. Consequently, in the case of the 0.1-ha opening there is a small increase in light in the opening (Figure 3) and this has little effect on air and soil temperature (Figure 11). In the larger openings, most of the transition from forest to clearcut occurs within about 10 m of the edge. The clearcut is warmer during the day and the same temperature as, or slightly cooler than, the forest at night (Appendix 3). The difference in daily mean temperature between the clearcut and forest is about 1°C at 1.5 m and 0.3°C at 0.2 m in the air and 0.5°C in the soil (Appendix 4). The differences in monthly mean air temperature between the forest and opening were about 1°C. There is greater variability in the soil temperatures, but the same patterns are evident. The difference in soil temperature between the clearing and forest is about 3°C.

As expected, the largest variation between positions occurs at the edge. After sunrise, the north edge (south-facing) warms quickly and is 3–5°C warmer during the early afternoon than any of the other three edges. By late afternoon, the north edge is

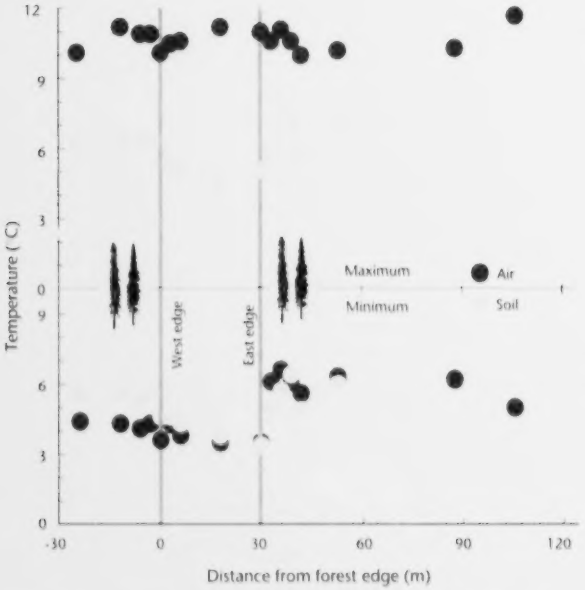

FIGURE 11 *Daily maximum and minimum air and soil temperature on a west–east transect from the forest through the 0.1-ha opening, September 30, 1997.*

shaded as the sun moves into the northwest quadrant. During the morning, the west and north edges are the warmest as they receive full sun. In the late afternoon, the east and south edges receive full sunshine and are warmest. Although the solar radiation received by the east and west edges is identical when integrated over a full day, the west edge does not become as warm in the morning as the east does in the afternoon. This effect is seen over a large range of scales from a single disk-trench up to a large valley—the maximum temperatures are higher on the slope that receives the afternoon sun because temperatures there have been increasing throughout the day before the full solar irradiance is incident.

The patterns in soil temperature are generally similar to those described for air temperature (Figures 9, 10, and 11 and Appendix 4). The amplitude of the soil temperature wave at 0.07 m is reduced and it lags the air temperature wave by about 3 hours. Differences in vegetation cover and soil moisture within the opening result in a large spatial variation in soil temperature.

5.2.9 Air and soil temperature profiles

Snow and vegetation cover influence the air temperature and soil temperature profiles. Maximum and minimum air temperatures occur close to the surface of each layer because these surfaces are where the energy exchange takes place. Typical profiles for sunny days are presented for a forest (near treatment block B5) in the summer and a large opening at the base weather station in the summer and winter. The daytime maximum temperature in the forest varied by only 2°C over 27 m (Figure 12), while the range was about 20°C over 6 m in an open area (Figure 13). The highest maximum temperature in the forest occurred at about 9 m above the ground. This tempera-

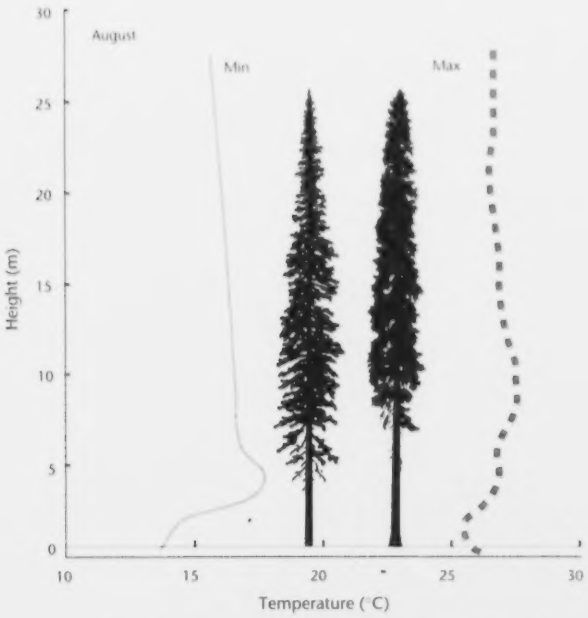

FIGURE 12 *Maximum and minimum air and near-surface soil temperature (°C) profiles for a clear day, August 5, 1997, in the forest near the 10-ha opening. This is the same day as for the large opening shown in the right-hand side of Figure 13.*

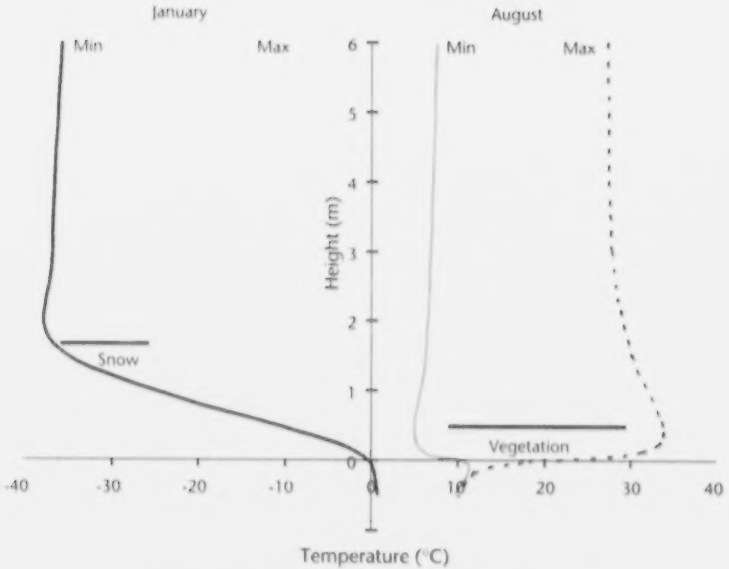

FIGURE 13 *Maximum and minimum air and soil temperature (°C) profiles for clear days, January 13 and August 5, 1997, in a large opening. Height of snowpack and vegetation indicated by horizontal lines.*

ture was similar to that of air well above the opening. The profile maximum occurred at 1 m into the opening. The shallower profile and higher point of maximum temperature in the forest is the result of the absorbed energy being distributed throughout the canopy rather than in a shallow layer at the surface, as occurs in the opening. The forest nighttime temperature profile had a similar shape to the daytime one, with a range of 3°C. The temperature increased from the soil to about 4 m and then decreased towards the top of the canopy. The opening shows a typical nighttime inversion with the lowest temperature close to the top of the vegetation (mainly grasses and forbs). The lower nighttime temperatures are a result of cold air draining from the treatment area and pooling in the valley. In the winter there is an air temperature inversion over the snowpack all the time. The snowpack has strong insulating properties so that in mid-winter the pack temperature increases with depth, and the soil temperature remains above freezing.

6 DISCUSSION

6.1 MICROCLIMATE OF FOREST, EDGE, AND OPENING

Much of the transition between the 22–27 m tall forest and openings at Sicamous Creek occurred within 20 m either side of the edge. Redding et al. (2003) found a similar effect in a soil moisture and temperature study conducted at Sicamous Creek in 2000. Results are consistent with a number of other studies listed in Table 1. These studies have shown that much of the change in microclimate takes place within a distance equal to the mean height of the dominant and co-dominant trees either side of the edge.

The conceptual model of edge microclimate described earlier is supported by published studies and the Sicamous results. Opening size is the most important variable through its control primarily on solar radiation in the opening and secondarily on wind flow. Circular or square openings of 1 ha (four to five tree heights wide at Sicamous) or greater have a microclimate typical of a larger open area over much of their area. Openings of less than 0.1 ha (about one tree height in diameter at Sicamous) have a microclimate similar to that of the forest. Carlson and Groot (1997), Potter et al. (2001), Stathers et al. (2001), and York et al. (2003) found similar results. The transition from forest to open conditions occurs quite rapidly as opening size increases above 0.1 ha. The conceptual model can be applied to openings that are strip cuts as long as an estimate of the radiation environment can be made (e.g., Halverson and Smith 1974). The CLIMO model (Chen et al. 1993) can be also be configured to approximate a strip cut. View factors calculated for longwave radiation (Riefsnyder and Lull 1965; Cochran 1969) can also be applied to solar radiation (Carlson and Groot 1997).

6.2 IMPLICATIONS OF SICAMOUS CREEK CLIMATE FOR PLANTS

In this wet subzone of the ESSF biogeoclimatic zone, cool air and soil temperatures and snow cover are the dominant fea-

tures of the environment. The growing season is cool, moist, and short, and snow cover exists for 8 months. Differences between forest and opening temperature were not large. Probably the biggest change that would be experienced by plants and animals between forest and openings is in the solar or photosynthetically active radiation regime. Vegetation flushes in mid- to late June at the site. The critical period for summer frost injury is the period between bud swelling and the end of shoot elongation. In contrast to the drier subzones of the ESSF, where frosts during this period are frequent and severe (Steen et al. 1990), there appears to be minimal danger of severe frost injury at the Sicamous Creek site. Considering the large amount of water from snowmelt and summer rainfall, and relatively low summer evaporative demand, it is unlikely that soil moisture stress is significant at this site in most years.

Conifers are most susceptible to UV-B injury during flushing and elongation when the wax cuticle is not fully developed. Lodgepole pine and mid- to high-elevation Engelmann spruce are relatively resistant to UV-B, requiring a constant daily dosage of 8 kJ m^{-2} d^{-1} (Green weighted, normalized at 300 nm) to cause some injury (L'Hirondelle and Binder 2002). The peak daily UV-B dosage at Sicamous Creek, with normal ozone column thickness, would be approximately 9.5, and the average daily dosage, approximately 5.5 kJ m^{-2} d^{-1} (Green weighted, normalized at 300 nm). The Sicamous Creek site has about two-thirds of the potential total solar radiation during the summer due to the high frequency of cloud. Thus it is unlikely that visible injury due to UV-B would occur even if ozone column thickness decreased by 20% (increasing UV-B irradiance by up to 40%).

Edge microclimate can influence plant growth. Huggard and Vyse (2002) report negative effect on tree growth on the south edge relative to the centre at Sicamous Creek. Brand et al. (2000) suggest that effects of openings on lichens and mosses extend some distance from the north edge.

6.3 IMPLICATIONS FOR FOREST HYDROLOGY

From a hydrologic perspective, the reduced interception of precipitation through forest removal increases the amount of

water available for streamflow. Snow disappears more rapidly in openings than in the forest, with the result that if sufficient area of a watershed is harvested there can be significant changes in the timing and volume of spring peak streamflow. The influence of the edge on the total amount of snowmelt from an opening will depend on the ratio of the edge opening area. It is likely that the small (0.1-ha) harvested openings had little effect on snow accumulation and snowmelt relative to the forest. This is because they have similar microclimates, and because stems in the forests are clumped, with many gaps similar in size to the openings.

7 SUMMARY

Results from this study are consistent with numerous other studies in different forest and climatic conditions. Much of the change in microclimate takes place within one mean height of the dominant and co-dominant trees on either side of the forest/opening edge. At Sicamous Creek this is 20–25 m either side of the edge.

Solar and photosynthetically active radiation

- Radiation below the canopy is 20–30% of above-canopy values.
- Openings of less than 0.1 ha (one tree height [25 m] wide or less) have radiation regimes similar to those of the forest.
- Openings of greater than 1 ha (>four tree heights [100 m] wide) have more than 75% of the opening with a radiation regime at the ground similar to that above the canopy.
- Edge effects on light extend to less than one tree height either side of the edge.
- North and south edges are not symmetrical.

Longwave radiation

- Edge effects extend to less than one tree height (25 m) either side of the edge.

Wind speed

- Openings of less than 0.1 ha have low wind speeds, similar to those of the forest.

- In larger openings, the wind variation away from the edge depends on the wind direction.

Precipitation

- The forest canopy intercepts 20–30% of the rain and snow.
- Edge effects on snow accumulation extend less than one tree height (25 m) into the clearcut.
- Snow accumulations are higher and snow disappears later at the shaded south edge of the opening.
- Snowmelt rates in late spring in large openings can be more than 50 mm d^{-1}.

Air temperature

- Openings of less than 0.1 ha have air temperatures similar to those of the forest.
- Large openings have maximum air temperatures 2–3°C greater than those of the forest. Minimum temperatures are similar to those of the forest.
- Edge effects in openings of greater than 1 ha extend up to one tree height (25 m) into the forest.
- Daily maximum and minimum air temperatures occur near the surface of the ground in openings and in the lower half of the canopy in the forest.

Air humidity

- The warmer daytime air temperature in the large opening results in the relative humidity being 5–10% lower than that in the forest.
- Edge effects on humidity are similar to those on air temperature.

Soil temperature

- Openings of less than 0.1 ha have soil temperatures similar to those of the forest.
- Large openings have maximum soil temperatures 4–6°C greater than those of the forest. Minimum temperatures are similar to those of the forest.
- Edge effects in large openings extend no more than one tree height (25 m) into the forest.

Soil moisture

- Edge effects extend to one tree height (25 m) either side of the edge.

APPENDIX 1 Instrumentation at the Sicamous Creek base camp weather station

Variable	Instrumentation	Height
Data logging	Campbell Sci. Inc. 21X , CR10, SM192 storage module	0.5 m
Power supply	12 V lead-acid battery and solar panel	0.5 m
Support for equipment	0.25-m triangular-lattice tower	6 m
Solar radiation	LiCor 200-S	6 m
Photosynthetically active radiation	LiCor 200-Q	6 m
Air temperature	Vaisala HMP-35C + shield	5.5 m
	Thermocouples in 3 mm diameter tubing + shield	3, 1.5, 0.25 m
Relative humidity	Vaisala HMP-35C + shield	5.5 m
Wind speed	Met One 013	6 m
Wind direction	Met One 024	6 m
Snow depth	Campbell Sci. Inc. UDG01	4 m
Rainfall	Sierra Misco model 2501	0.5, 1 m
Soil temperature	Thermocouples potted in 6-mm stainless steel tubing	0.01, 0.15, 0.5 m

FIGURE A1.1 *Sicamous Creek base camp weather station in July 2002.*

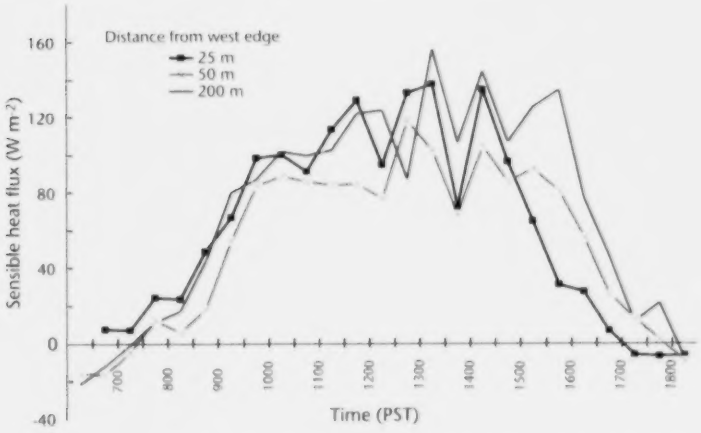

FIGURE A2.1 *Sensible heat flux at 25 m (■), 50 m (◦), and 200 m (—) from the west edge in the BS opening, August 20, 1997.*

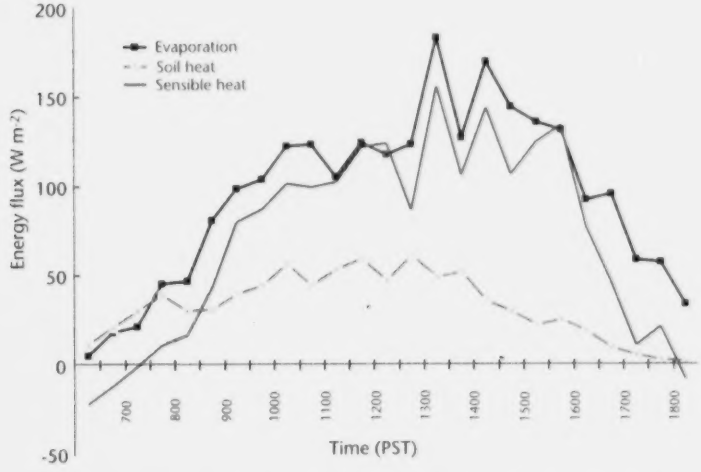

FIGURE A2.2 *Evaporation (■), sensible heat flux (—), and soil heat flux (◦) at the 200 m point of the west–east transect in the BS opening, August 20, 1997.*

APPENDIX 3 Daily maximum and minimum air temperature in the 10-ha opening

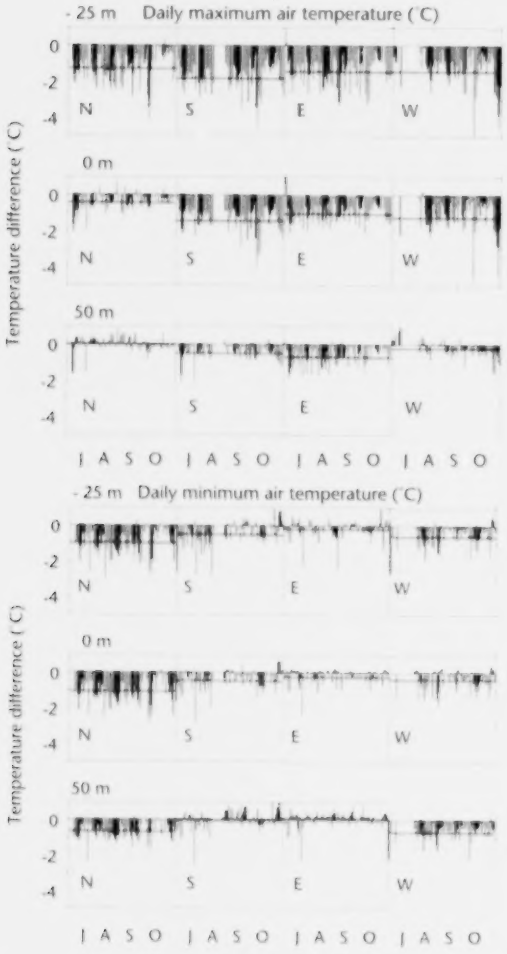

FIGURE A3.1 *Difference in daily maximum (upper panel) and minimum air temperature (lower panel) at 1.5 m above the ground between transect locations for all four edges and the middle of the 10-ha opening from July to October 1997. -25 m is in the forest, 0 m is the forest edge, and 50 m is in the opening. The grey horizontal line is the average difference.*

APPENDIX 4 Air and soil temperature transects across the edge of the 10-ha opening

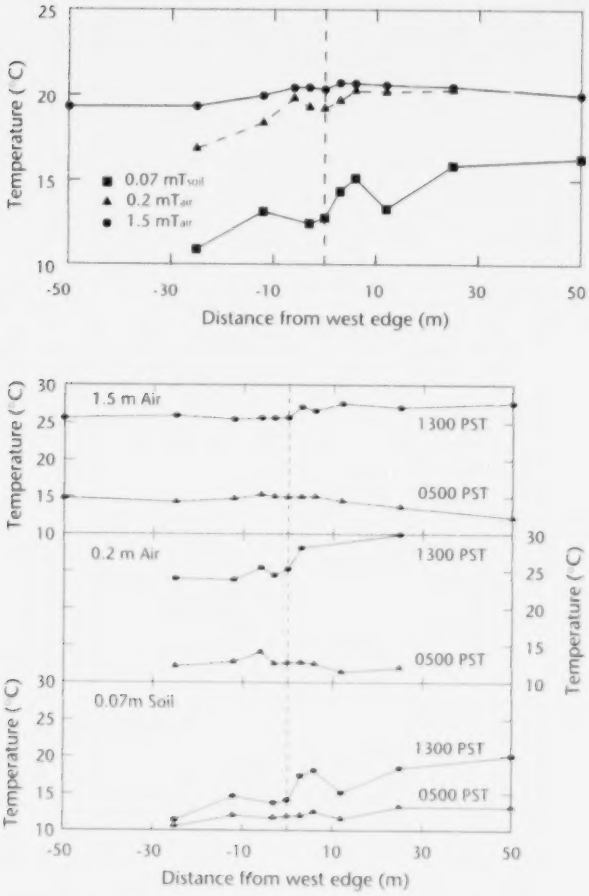

FIGURE A4.1 *Transects of daily mean air and soil temperatures (upper panel) across the west edge and temperature at 1300 and 0500 PST (lower panel) on August 5, 1997. This day was the hottest day recorded in 1997. Winds were calm and solar irradiance was high, conditions that should give rise to the greatest variations in temperature across the edge. Negative distances are in the forest.*

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